Understanding advances and challenges of urban water security and sustainability in China based on water footprint dynamics

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Abstract

Sustainability of China's numerous cities are threatened by both quantity- and quality-induced water scarcity, which can be measured by the water footprint from a consumption (WFcons) or production (WFprod) perspective. Although WFcons was widely assessed, the changes in WFprod of China's cities were still unclear. Taking 31 major cities as examples, this study revealed the dynamics of urban WFprod in China from 2011 to 2016. First, the spatiotemporal patterns of WFprod and water deficit were evaluated and then the main reasons for the WFprod dynamics and its implications for urban sustainability were explored. A large-scale decrease in urban WFprod in China was found, with the average WFprod decreasing from 13.8 billion m^3 to 10.3 billion m^3 and the per capita WFprod decreasing from 1614.8 m^3/person to 1184.0 m^3/person (i.e., falling by more than a quarter in just six years). Such shrinkage was particularly evident in drylands, eliminating the water deficit in Xi'an and Xining. The reduction in grey WFprod caused by implementing water pollution prevention policies and other relevant measures played the most important role in the savings. In the future, the implementation of updated pollution discharge standards is projected to allow more cities to escape water deficits; however, the rapid growth of the domestic and ecological blue WFprod caused by urbanization and urban greening would destabilize this prospect. Thus, attention should be given to both water pollution prevention and domestic and ecological blue WFprod restriction to further alleviate urban water scarcity in China.

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Understanding advances and challenges of urban water security and sustainability in China based on water footprint dynamics

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Key points:

More than a quarter decrease in urban water footprint from production perspective in China from 2011 to 2016.

The policy-induced rapid reduction in grey water footprint was found.

The growth of domestic and ecological blue water footprint needs more attentions.

Abstract: Sustainability of China's numerous cities are threatened by both quantity- and quality-induced water scarcity, which can be measured by the water footprint from a consumption (WF_{cons}) or production (WF_{prod}) perspective. Although WF_{cons} was widely assessed, the changes in WF_{prod} of China's cities were still unclear. Taking 31 major cities as examples, this study revealed the dynamics of urban WF_{prod} in China from 2011 to 2016. First, the spatiotemporal patterns of WF_{prod} and water deficit were evaluated and then the main reasons for the WF_{prod} dynamics and its implications for urban sustainability were explored. A large-scale decrease in urban WF_{prod} in China was found, with the average WF_{prod} decreasing from 13.8 billion m^3 to 10.3 billion m^3 and the per capita WF_{prod} decreasing from 1614.8 m^3 /person to 1184.0 m^3 /person (i.e., falling by more than a quarter in just six years). Such shrinkage was particularly evident in drylands, eliminating the water deficit in Xi'an and Xining. The reduction in grey WF_{prod} caused by implementing water pollution prevention policies and other relevant measures played the most important role in the savings. In the future, the implementation of updated pollution discharge standards is projected to allow more cities to escape water deficits; however, the rapid growth of the domestic and ecological blue WF_{prod} caused by urbanization and urban greening would destabilize this prospect. Thus, attention should be given to both water pollution prevention and domestic and ecological blue WF_{prod} restriction to further alleviate urban water scarcity in China.

Keywords: urban landscape sustainability; water security; water scarcity; water pollution; water demand

1 Introduction

In recent decades, urbanization has been one of the most important socioeconomic processes in China, with the urban population increasing from 60 million (10.6% of the total population) to 900 million (63.9%) between 1950 and 2020 (China Statistical Yearbook, 2021). Cities are increasingly consuming resources, generating waste and pollution, and causing environmental and social problems that are central to sustainable development (Bai et al., 2014; Yue et al., 2020; Kuang, 2020;

Wiedmann and Allen, 2021). With the growth of the urban population, the rapid development of the economy and the continuous improvement of cultivated land-use intensity, the contradiction between urban water supply and demand is intensifying, resulting in more serious urban water scarcity and pollution in China (Yu et al., 2019; Liu et al., 2020; Ma et al., 2020a, 2020b; Ye et al., 2020; He et al., 2021; Jiang et al., 2021). This hinders the achievement of sustainable cities and threatens residential health, environmental quality, and economic growth (Florke et al., 2013, 2018; McDonald et al., 2016; Nazemi and Madani, 2018; Yu, 2019; Wang et al., 2022). In order to address these issues, it is important to understand the spatiotemporal patterns of urban water scarcity and pollution and their influencing factors for improving urban sustainability in China (Wu, 2014).

The water footprint (WF) refers to the amount of water consumed to produce goods and services on an individual, regional, or global level, at a given time (Hoekstra, 2003; Hoekstra and Huang, 2002). The WF consists of the blue WF, the green WF and the grey WF. The blue WF represents the use of surface and ground water; the green WF refers to the consumption of rainwater, insofar as it does not become run-off; and the grey WF represents the use of freshwater required to dilute polluted water to meet existing water quality standards (Hoekstra et al., 2011). Compared to other water scarcity indicators, the WF is able to assess water scarcity induced by both water quantity (blue WF and green WF) and quality (grey WF) (Hoekstra, 2009; Paterson et al., 2015; Liu et al., 2017; Wu, 2021). As a result, the WF is widely used in the assessment of water scarcity in different global cities. For example, Chini et al. (2017) quantified the WF of 74 metropolitan cities in the USA and determined an average urban WF of 6,200 m^3/person per year. Souza et al. (2021) assessed the blue and grey WF and projected the potential future WF of San Carlos, Brazil, finding that the grey WF could be 35 times higher than the blue WF, and that the city would face a severe water quality-based water shortage. Fang et al. (2018) used the blue and grey WF to assess water resource utilization in Guiyang, China, and found that Guiyang's WF has exceeded the amount of available water resources leaving the city facing water shortages. These studies support that the WF provides an effective way to comprehensively evaluate urban water scarcity.

Recently, urban water scarcity assessments based on the WF have been carried out in China across multiple scales. On the national scale, Cai et al. (2019) evaluated the change in the WF of Chinese urban residents from a consumption perspective from 1992 to 2012. Wang et al. (2021) assessed the grey WF of 295 cities in China in 2016. At the basin or regional scale, Li et al. (2018) calculated the blue and grey WF of 26 cities in the Haihe basin. Zhao et al. (2017) comprehensively assessed the blue, green and grey WF of the Beijing-Tianjin-Hebei region. At the local scale, Zeng and Liu. (2013) quantified the trend of the grey WF in Beijing from 1995 to 2009.

However, existing studies still have some limitations. First, most of the studies focused on individual cities (e.g., large and economically developed cities such as Beijing and Shanghai) or urban agglomerations (Zhang et al., 2012; Zhao et al., 2017), and there are few studies on cities across China. Second, most of the studies only assessed urban water scarcity induced by water quality or water quantity (considering only blue WF or grey WF) (Wang et al., 2021; Zeng and Liu, 2013), lacking an integrated assessment of both quantity- and quality-induced water scarcity. In addition, most studies calculated the urban WF from a consumption perspective by assessing the number of water resources included in goods and services consumed by urban residents, which does not effectively reflect the local water resources used by cities for production, making it difficult to fully reflect the urban water scarcity (Li and Han, 2018; Cai et al., 2019). There is therefore a need to develop a production-based assessment of the WF of cities across China in terms of both the blue and grey WFs to fill these gaps in existing studies.

This study aims to assess the dynamics of the production-based WF of 31 major cities in China from 2011 to 2016 and to quantify the urban water scarcity in these cities by comparing the WF with available water resources. First, based on statistical data, the spatiotemporal patterns were quantified and the composition of the blue and grey WFs of China's major cities was determined. Then, the urban water deficit based on the WF and available water resources was quantified. On this basis, the influencing factors of the dynamic changes in the WF of these major Chinese cities and the implications for urban sustainability were determined. The results of the study provide a reference for the formulation of urban water-saving policies and the delineation of pollution discharge standards, thereby promoting water security and sustainable development for China's major cities.

2 Study area and data

2.1 Study area

The study focuses on 31 major cities in mainland China, including municipalities, capitals of provinces and autonomous regions (Taipei, Hong Kong and Macao were not selected due to lack of data; Figure 1). In 2016, the total population of these cities reached 280 million, accounting for 34.2% of the total urban population in China. From 2011 to 2016, the study area experienced rapid socioeconomic development and a rapid increase in per capita GDP, with the average per capita GDP increasing from 54,000 RMB to 84,000 RMB, an increase of 55.3%. According to the *Water Pollution Prevention and Control Plan for Key River Basins (2011-2015)*, jointly issued by China's Ministry of Environmental Protection, Development and Reform Commission, Ministry of Finance and Ministry of Water Resources, cities are divided into cities within the pollution control basin (17 cities) and other cities outside the basin (14 cities).

<Insert Fig. 1 here>

2.2 Data

The industrial chemical oxygen demand (COD) emissions, industrial ammonia nitrogen emissions and industrial wastewater discharge were used to calculate the industrial grey WF of the major cities. The domestic COD emissions, domestic ammonia nitrogen emissions and domestic wastewater emissions were obtained from the 2012-2017 China Statistical Yearbook and were used to calculate the domestic grey WF.

The industrial water consumption of major cities was used to calculate the industrial blue WF. The urban domestic water consumption and urban public water consumption of major cities were used to calculate the domestic blue WF. The ecological and environmental water consumption of major cities was used to calculate the ecological blue WF. These data were obtained from the 2011-2016 Water Resources Bulletins of provinces, autonomous regions and municipalities. The Water Resources Bulletins for Heilongjiang Province, Hainan Province and the Tibet Autonomous Region were not publicly available, so data on the blue WF of Harbin, Haikou and Lhasa were not available. The Water Resources Bulletins for Ningxia Hui Autonomous Region lacks data on urban environmental water use, so the ecological blue WF for Yinchuan is not available.

The year-end resident population data of selected cities, which were used to calculate the per capita WF, were obtained from the 2012-2017 China Urban

Statistical Yearbook. The amount of available water resources (including surface water resources, subsurface water resources, inter-basin water transfer and water from upstream, with the duplication of surface water and groundwater removed), were used to assess the water scarcity of major cities. The data was obtained from the 2011 to 2016 Water Resources Bulletin of provinces, autonomous regions and municipalities.

When calculating the WF, the grey WF was not comparable due to the large difference in urban sewage discharge data before and after 2011 in the China Statistical Yearbook. In addition, the China Statistical Yearbook after 2017 no longer counted the emissions of ammonia nitrogen and other pollutants in major cities. Thus, this study only assessed the WF dynamics of China's major cities from 2011 to 2016.

3 Methods

3.1 Calculating the WF

Referring to the studies of Li et al. (2018) and Fang et al. (2018), the urban WF was expressed as the sum of the grey and blue WF, taking into consideration that there is almost no agricultural green water consumption in urban areas. Among them, the grey WF includes two parts: industrial grey WF and domestic grey WF. The blue WF includes three parts: industrial blue WF, ecological blue WF and domestic blue WF (Table 1, Figure 2). The calculation of the urban WF can be expressed as follows:

$$WF = WF_{grey} + WF_{blue} \tag{1}$$

where WF represents the urban WF, WF_{grey} represents the urban grey WF and WF_{blue} represents the urban blue WF.

<Insert Table 1 here>

<Insert Fig. 2 here>

3.1.1 Calculating the grey WF

The urban grey WF can be expressed as:

$$WF_{grey} = WF_{grey,ind} + WF_{grey,dom} \tag{2}$$

where $WF_{grey,ind}$ represents the industrial grey WF and $WF_{grey,dom}$ represents the domestic grey WF.

COD and ammonia nitrogen are the main pollutants in urban wastewater, and since water bodies are capable of diluting both ammonia nitrogen and COD, the larger value of the gray WF caused by ammonia nitrogen or COD is usually selected as the regional gray water footprint (Zeng and Liu, 2013), and the urban grey WF can be expressed as:

$$WF_{grey,i} = \max\left(WF_{COD,i}, WF_{NH3-H,i}\right) \tag{3}$$

where *i* refers to the footprint that comes from industrial or domestic sources. $WF_{COD,i}$ represents the amount of water required to purify the water quality of industrial or domestic wastewater to meet the COD discharge standard. $WF_{NH3\text{-}H,i}$ represents the amount of water required to purify the water quality of industrial or domestic wastewater to meet the ammonia nitrogen discharge standard.

The amount of water required to dilute a pollutant is expressed as (Cui et al., 2020):

$$WF_{COD,i} = \frac{L_{COD.i}}{C_{max,COD} - C_{nat}} - V_i \tag{4}$$

$$WF_{NH3-H,i} = \frac{L_{NH3-H.i}}{C_{max,NH3-H} - C_{nat}} - V_i \tag{5}$$

where $L_{COD,i}$ and $L_{NH3\text{-}H,i}$ represent the discharge of COD and ammonia nitrogen in domestic or industrial wastewater, respectively; $C_{max,COD}$ and $C_{max,NH3\text{-}H}$ represent the maximum concentration of COD and ammonia nitrogen that the environment can tolerate, respectively; C_{nat} denotes the initial concentration of COD and ammonia nitrogen in natural water bodies, and V_i denotes the discharge of industrial or domestic wastewater. According to China's *Standard Limits for Basic Items of Surface Water Environmental Quality Standards* (GB 3838-2002), which classifies surface water into five categories, Category III water is defined as "mainly applicable to secondary protected areas of surface water sources for centralized domestic drinking water, fish and shrimp overwintering grounds, migratory channels, aquaculture areas and other fisheries waters and swimming areas". Following Category III, $C_{max,COD}$ and $C_{max,NH3\text{-}H}$ were therefore adopted as the standard concentrations of COD at 20 mg/L and ammonia at 1 mg/L, respectively. C_{nat} is assumed to be 0 in reference to existing studies (Zeng and Liu, 2013).

The urban per capita grey WF is more comparable among different cities than the total urban grey WF. Thus, the per capita urban grey WF is further calculated for each city as:

$$WF_{grey,cap} = \frac{WF_{grey}}{pop} \tag{6}$$

where $WF_{grey,cap}$ represents the per capita grey WF and *pop* represents the local year-end resident population in one city.

3.1.2 Calculating the blue WF

The calculation of the urban blue WF can be expressed as:

$$WF_{blue} = WF_{blue,dom} + WF_{blue,ind} + WF_{blue,eco} \tag{7}$$

$$WF_{blue,dom} = WU_{blue,dom} \tag{8}$$

$$WF_{blue,ind} = WU_{blue,ind} - W_{Rec,ind} \tag{8}$$

$$WF_{blue,eco} = WU_{blue,eco} - W_{Rec,eco} \tag{9}$$

where $WF_{blue,dom}$ represents the domestic blue WF, $WF_{blue,ind}$ represents the industrial blue WF, and $WF_{blue,eco}$ represents the ecological blue WF. $WU_{blue,dom}$ represents the total water for domestic use by urban residents and for urban public use. $WU_{blue,ind}$ represents the total water used in urban industrial sectors. $W_{Rec,ind}$ represents the recycled water used in industrial sectors. $WU_{blue,eco}$ represents the total water use in urban environment and ecological replenishment, which is supplied by anthropogenic measures. $W_{Rec,ind}$ represents the recycled water used in urban environment and ecological replenishment.

The per capita blue WF calculation is expressed as:

$$WF_{blue,cap} = \frac{WF_{blie}}{pop} \tag{10}$$

where $WF_{blue,cap}$ represents the blue WF per capita.

3.2 Calculating the water deficit

The amount of water resources available for a city includes four components: surface water resources, subsurface water resources, inter-basin water transfer and water from upstream, while the water used by the agricultural sector should be removed. Therefore, the amount of per capita water available in cities can be expressed as:

$$WA = WA_{surface} + WA_{subsurface} + WA_{t} + WA_{up} - WA_{agr} \tag{11}$$

$$WA_{cap} = \frac{WA}{pop} \tag{12}$$

where WA represents available water resources, $WA_{surface}$ represents surface water resources, $WA_{subsurface}$ represents subsurface water resources, WA_{t} represents inter-basin transfers, WA_{up} represents upstream water, WA_{agr} represents water use in the agricultural sector, and WA_{cap} represents per capita water resources available.

Water deficit (WD) is a concept that arises in analogy to ecological deficit and can be used to measure water scarcity (Fang and Duan, 2015; Flörke et al., 2018). The water deficit is expressed as the difference between the amount of water available resources and the WF:

$$WD = WF - WA \tag{13}$$

where *WD* represents the water deficit. When the WF is greater than the available water resources, there is a water deficit, the city's available water resources cannot meet the city's water use and water purification needs, and the city has a water shortage. Conversely, a water surplus is indicated.

3.3 Analysis of the spatiotemporal patterns of the WF

Based on the research idea of the "pattern-process-relationship", the spatial pattern of the total WF, sectoral WF and water deficit of major cities in China in 2016 were quantified and then the dynamic changes in the total WF, sectoral WF and water deficit of these cities from 2011 to 2016 were quantitatively analysed. Finally, referencing Xu et al. (2020), the interrelationships between different sectoral WFs using Pearson correlation analysis were revealed.

4 Results

4.1 WF of major cities in China in 2016

In 2016, the average WF of major cities in China was 10.3 billion m^3, with a per capita WF of 1,184.0 m^3/person. The grey WF accounted for an obviously larger proportion than the blue WF, with 31 major cities having an average grey WF of 8.8 billion m^3, accounting for 85.0% of the total WF (Figure 3a). The domestic grey WF was larger than the industrial grey WF. Thirty-one major cities had an average domestic grey WF of 8.2 billion m^3, accounting for 94.1% of the grey WF, while the average industrial grey WF was 524.5 million m^3, accounting for only 5.9% of the grey WF (Figure 3b). The industrial blue WF and domestic blue WF accounted for a high proportion, while the ecological blue WF was low. Twenty-eight major cities with a blue WF had an average industrial blue WF and domestic blue WF of 860.4 million m^3 and 718.5 million $m^{3,}$ respectively, accounting for 50.5% and 42.2% of the blue WF, while the average ecological blue WF was 124.1 million m^3, accounting for only 7.3% of the blue WF (Figure 3b).

The WF of different cities varied (Figure 3c, Figure 3d), with Shanghai with the highest WF with 44.2 billion $m^{3,}$ and Chongqing and Guangzhou with WFs greater than 20 billion m^3, and values of 41.0 billion m^3 and 25.0 billion m^3, respectively. 15 major cities, such as Tianjin and Wuhan, had a WF of between 5 and 20 billion m^3, while the remaining 13 major cities had a WF of less than 5 billion m^3. Lhasa had the lowest WF of only 1.4 billion m^3, which was only 3.3% of Shanghai's WF (Figure 3c). There were also obvious differences in the per capita WF of different cities. Lhasa had the highest per capita WF at 2195.6 m^3/person, 20 major cities, such as Shanghai and Guangzhou, had a WF between 1000-2000 m^3/person, the remaining 10 major cities had a per capita WF of less than 1000 m^3/person, and Beijing had the lowest per capita WF at 338.7 m^3/person (Figure 3d).

Ten of the major cities had a water deficit. In terms of spatial distribution, cities with water deficits were mainly located in northern China (Figure 4). Tianjin had the largest water deficit at 13.5 billion m^3, followed by Zhengzhou and Shenyang with 8.7 billion m^3 and 6.2 billion m^{3,} respectively, while the remaining seven cities had a water deficit of less than 5 billion m^3.

<Insert Fig. 3 here>

<Insert Fig. 4 here>

4.2 Changes in the WF of major cities in China

From 2011 to 2016, the average WF of China's major cities decreased obviously, with the grey WF decreasing more than the blue WF (Figure 5). During this period, the average WF of major cities decreased from 13.8 billion m^3 to 10.3 billion m^3, a decrease of 3.5 billion m^3. The average grey WF decreased from 12.1 billion m^3 to 8.8 billion m^3, a decrease of 3.3 billion m^3, accounting for 96.5% of the decrease in WF; the average blue WF decreased from 1.8 billion m^3 to 1.7 billion m^3, a decrease of 0.1 billion m^3 (Figure 5a). Within the grey WF, the domestic grey WF decreased obviously more than the industrial grey WF. The average domestic grey WF of major cities decreased from 10.8 billion m^3 to 8.2 billion m^3, a decrease of 2.6 billion m^3, accounting for 75.7% of the average grey WF reduction (Figure 5b). Within the blue WF, the domestic blue WF and ecological blue WF increased, and the industrial blue WF decreased, but none of the changes were obvious. The average domestic blue WF and ecological blue WF of major cities increased from 615.4 million m^3 and 79.7

million m^3 to 718.5 million m^3 and 124.1 million m^3, respectively, an increase of 103.2 million m^3 and 44.4 million m^{3,} respectively, and the industrial blue WF decreased from 1141.7 billion m^3 to 860.4 million m^3, a decrease of 281.3 million m^3 (Figure 5b).

Changes in the WF varied obviously between cities (Figure 5c, Figure 5d). Thirty (96.8%) of the major cities saw a decrease in their WF, and only Lhasa had an increase in WF. Shanghai and Beijing had the largest decrease in WF, from 54.5 billion m^3 and 17.6 billion m^3 to 44.2 billion m^3 and 7.4 billion m^3, respectively, both decrease of 10.3 billion m^3. 7 cities, such as Xi'an and Shenyang, had a decrease in WF between 5 and 10 billion m^3; and 20 cities, such as Changchun and Tianjin, had a decrease of less than 5 billion m^3. Lhasa had an increase of 0.4 billion m^3 in WF. The difference in the per capita WF of different cities was also obvious (Figure 5c). Thirty (96.8%) of the major cities experienced an obvious reduction in their per capita WF, while only one city (Lhasa) experienced an increase. Lanzhou, Yinchuan and Xi'an were the cities with the largest decreases in per capita WF, with decreases greater than 1000 m^3/person; 6 cities, such as Shenyang and Urumqi, had decreases in per capita WF between 500-1000 m^3/person; and 21 cities, such as Beijing and Chengdu, had decreases in per capita WF less than 500 m^3/person. Only the per capita WF of Lhasa increased, from 1751.6 m^3/person to 2195.6 m^3/person, an increase of 444.0 m^3/person (Figure 5d).

Among the 28 cities with full WF data, the obvious decrease in grey WF is still the main reason for all cities. Specifically, 15 (53.6%) cities, such as Changsha and Hangzhou, saw a decrease in their grey WF and blue WF, with the grey WF decreasing obviously more than the blue WF. The other 13(46.4%) cities, such as Jinan and Nanning, saw an obvious decrease in their grey WF while their blue WF increased, but the increase was less than the decrease in their grey WF.

From 2011 to 2016, water shortages in major cities eased (Figure 6). The number of cities with a water deficit decreased from 12 to 10, with Xi'an and Xining no longer having the water deficit. All the 10 major cities that still have a water deficit have reduced their water deficit. Beijing and Shenyang were the cities with the largest decreases in water deficit, with water deficit decreasing by more than 5 billion m^3. Changchun, Tianjin, Yinchuan and Shijiazhuang had water deficit decreasing by 2.5 to 5 billion m^3. Zhengzhou, Taiyuan, Urumqi and Hohhot had water deficit decreasing by less than 2.5 billion m^3.

<Insert Fig. 5 here>

<Insert Fig. 6 here>

4.3 Urban WF along the precipitation gradient

The per capita WF of major cities showed a "U" curve along the precipitation gradient (Figure 7a). The average per capita WF of the 4 major cities with average annual precipitation within 200-400 mm (Hohhot, Yinchuan, Urumqi and Lanzhou) was 1518.3 m^3/person, 28.2% higher than the average per capita WF of all major cities. The average per capita WF of the 14 major cities with average annual precipitation between 400-1000 mm is 939.6 m^3/person, 20.6% lower than the average per capita WF of all major cities. The average per capita WF of the 13 major cities with average annual precipitation greater than 1000 mm rises again to 1344.4 m^3/person, which is 13.5% higher than the average per capita WF of all major cities (Figure 6a).

The WF of major cities decreased less with increasing precipitation, and the difference in urban WF within the same precipitation gradient decreased (Figure 7b). The 4 major cities with average annual precipitation within 200-400 mm (Hohhot, Yinchuan, Urumqi and Lanzhou) had an average per capita WF reduction of 878.3 m^3/person, with Lanzhou having the largest reduction of 1498.0 m^3/person. The 3 major cities with average annual precipitation within 1400-1600 mm (Guangzhou, Haikou and Fuzhou) saw their average per capita WF decrease by 303.2 m^3/person, with Nanchang seeing the least reduction of 141.6 m^3/person.

<Insert Fig. 7 here>

4.4 Relationships between grey WF and blue WF

There was a significant positive correlation between the per capita blue WF and the per capita grey WF in major cities in 2016, with a correlation coefficient of 0.42 ($p< 0.05$, Figure 8a). For example, Guangzhou was the city with the largest per capita blue WF, with a per capita blue WF of 392.0 m^3/person, 2.6 times higher than the average per capita blue WF, while Guangzhou had a similarly high per capita grey WF of 1422.8 m^3/person, 37.8% higher than the average per capita grey WF. Beijing was the city with the lowest per capita grey WF, with a grey WF of 234.18 m^3/person, which was only 22.7% of the average per capita grey WF. The per capita blue WF in Beijing was also very low, 104.5 m^3/person, which was only 68.9% of the average per capita blue WF.

There was no significant correlation between changes in the WF of the major cities, with a correlation coefficient of only 0.019 and failing the significance test (Figure 8b). For example, Lanzhou had the largest reduction in the per capita grey WF, with a reduction of 1464.8 m^3/person between 2011 and 2016, 3.5 times the average reduction in the per capita grey WF of major cities, but the reduction in the blue WF in Lanzhou was not obvious, with a reduction of only 33.1 m^3/person. Fuzhou had the largest reduction in the blue WF, with a reduction of 189.0 m^3/person, 12.1 times the average reduction in the per capita blue WF of major cities, but the reduction in the grey WF of Fuzhou was small, with a reduction of 178.4 m^3/person, only 43.0% of the average reduction in the per capita grey WF of major cities.

<Insert Fig. 8 here>

5 Discussion

5.1 Comparison between production-based versus consumption-based WF

This study quantified the dynamics of the production-based WF (WFprod) of major Chinese cities and is an important addition to the existing consumption-based WF (WFcons) studies (Table 2). Compared to the WFcons (2826.5 m^3/person in 2012) of Chinese cities quantified by Cai et al. (2019), the quantified WFprod (1618.6 m^3/person in 2011) in this study is obviously lower. The main reason for this is that the WFcons estimates the amount of water consumed in the goods and services consumed by urban residents, while the food and many other goods and services consumed by urban residents come from outside the city. In contrast, WFprod estimates the amount of water consumed in the production of goods and services in the city. By comparing the differences between the two, the amount of water resources consumed by the products and services that cities import through trade can be further analzyed to reveal the extent to which cities rely on extraterritorial water resources. The study by Cai et al. (2019) also shows that China's urban WFcons declined obviously from 1992 to 2012, which is the same trend as the change in the WFprod found in this study, indicate the factors that led to a reduction in the urban WF, including a cities' transformation of the industrial structures on the production side, the reduction of pollution emissions and the change in consumption structures.

Compared to the foreign urban WF, in terms of both the WFprod and the WFcons calculated by Cai et al. (2019), China's urban per capita WF was obviously lower than that of US cities (Chini et al., 2017) and higher than that of cities in Egypt and Colombia (Wahba et al., 2018; Castilla et al., 2018). The results of Hoekstra and Chapagain (2006) also showed that China's per capita WF from 1997 to 2001 was lower than that of developed countries, such as the United States and Canada, and close to that of developing countries, such as India and South Africa, with the lowest WF among the 23 countries assessed. International comparisons show that China's per capita water consumption by urban residents was generally low, with room for further decline.

<Insert Table 2 here>

5.2 Main influencing factors for changes in WF

As shown, the urban WF is influenced by a combination of the urban environment, socioeconomic status, governance and technology (Figure 9a). In general, cities with more precipitation have more available water resources and a higher blue WF (Veettil and Mishra, 2018). Meanwhile, urban climatic conditions and greening rates combine to influence the ecological blue WF; urban green spaces in wet areas tend to rely on rainwater, and the relationship between WF and change in green space is not significant, but the ecological blue WF in dry areas increases significantly with increased green space areas (Nouri et al., 2019). Our results show that the ecological blue WF is positively correlated with the greening rate significantly in cities with an annual precipitation of less than 800mm (a dividing line of balance between precipitation and evaporation), while the ecological WF is not significantly correlated with the greening rate in cities with an annual precipitation of more than 800mm (Figure 9b).

<Insert Fig. 9 here>

The impacts of socioeconomic status on the WF are more complex. On the one hand, the transition from agriculture to industry usually leads to an increase in industrial water use and industrial pollution, increasing the industrial blue WF and industrial grey WF. On the other hand, industrial upgrading and the transition from industry to services implies a shift from high-energy-using and high-polluting industries to low-energy-using and low-polluting industries, with increased water use efficiency and reduced pollution, which will reduce the WF (Zhang et al., 2020; Liu et al., 2021). Both of these pathways were reflected in this study. As shown in the Figure 9c, the domestic WF (including domestic blue WF and domestic grey WF) of major cities increases with the increase GDP of service industry ($R=0.68$, $P<0.01$). However, Beijing is an exception. The GDP of service industry in Beijing is the highest, but the domestic WF is very low, which is closely related to the active promotion of reclaimed water use and pollution control (see below). In addition, our findings show that the per capita WF of 30 major cities in China declined from 2011 to 2016, as their economic development and per capita GDP increased, with only Lhasa increasing its per capita WF (Figure 5a). This indicates that economic development has contributed to the improvement of environmental quality, obviously reducing the grey WF by controlling pollution emissions. However, it is worth noting that the per capita blue WF of major cities has an obvious positive correlation with per capita GDP, and the per capita blue WF of some cities continues to increase (Figure 5a, Figure 9d), which indicates that the economic growth of major cities in China is accompanied by a large consumption of blue water resources, especially the domestic blue WF and ecological blue WF, which have obviously increased. Although some urban green spaces do not need irrigation, with further urban expansion and greening, coupled with global warming and urban heat island, it is likely to further increase the demand for domestic blue WF and ecological blue WF.

Governance is also an important factor influencing the WF, with water saving policies reducing water usage and the implementation of pollution control policies reducing discharges from the industrial and domestic sectors (Zhang et al., 2020). The implementation of water pollution control policies can greatly decrease the urban WF (Figure 9e), with the average grey WF of the 17 major cities within pollution control basins decreasing from 12.2 billion m^3 in 2011 to 7.9 billion m^3 in 2016, a decrease of 4.3 billion m^3 (35.1%). In contrast, the remaining 14 major cities, not in pollution control basins, had an average WF decrease from 12.1 billion m^3 to 9.8 billion m^3, a reduction of only 2.3 billion m^3 (18.9%). Water pollution control policies have reduced the grey WF by requiring cities to invest in wastewater treatment plants, increasing domestic wastewater treatment rates and raising water pollutant discharge standards. For example, the *Water Pollution Prevention and Control Plan for Key River Basins (2011-2015)* requires that all cities in pollution control basins should build sewage treatment plants, the sewage treatment rate in major cities should reach over 85%, and urban sewage treatment plants should ensure that they meet Class I B discharge standards (GB 18918-2002, with ammonia nitrogen concentrations below 8 mg/L and COD concentrations below 60 mg/L) by 2015.

Technological development can increase water use efficiency, waste water recycling capacity and pollution treatment capacity. Waste water recycling capacity and pollution treatment capacity are both important technologies for reducing WF (Zhang et al. 2014). From 2013 to 2015, 47 new reclaimed water treatment plants were built in Beijing, and reduced its blue WF by 1 billion m^3 in 2016. Meanwhile, 20 wastewater treatment plants were upgraded in Beijing, and the city's wastewater treatment capacity increased to 6.72 million m^3/day. In contrast, the sewage treatment capacity of Xining in the same period was only 0.33 million m^3/day. Therefore, although Beijing's population and GDP were 20.1 and 9.4 times of Xining's population and GDP, respectively, Beijing's gray WF was only 1.3 times of Xining's gray WF. This suggests that applying technologies that have been well established in Beijing to other cities can further reduce the WF of these cities.

5.3 Implications for achieving urban water security and sustainability

These findings confirm that water pollution control policies are effective in reducing the WF, and that the policies should be implemented more rigorously in the future to further reduce the WF. Following the implementation of the *Water Pollution Prevention and Control Plan for Key River Basins (2011-2015)* (the *Plan* for short), water shortages in China's major cities eased. The number of cities with water deficits decreased from 12 to 10, with water deficits disappearing in Xi'an and Xining. However, as of 2016, there were still 10 cities that still did not meet the *Plan*'s water pollutant treatment capacity (Figure 10a). If these 10 cities met the standards set by the *Plan*, the water deficit in Beijing, Urumqi, Changchun, Shenyang and Shijiazhuang would be eliminated (Figure 10a). In 2017, the State Ministry of Environmental Protection, the Development and Reform Commission and the Ministry of Water Resources jointly updated the *Plan* for the *Water Pollution Prevention and Control Plan for Key River Basins* (2016-2020) (the *New Plan* for short). The *New Plan* requires that by 2020, the country would have increased its daily sewage treatment capacity by 45 million tons, that all counties and key towns would have sewage collection and treatment capacity, and the urban sewage treatment rate would reach 95%. By 2018, urban wastewater discharge standards in key river basins would reach Class A discharge standards (ammonia nitrogen concentration below 5 mg/L and COD concentration below 50 mg/L). If the new regulations are implemented, Tianjin will eliminate its water deficit (Figure 10a). Therefore, major Chinese cities should strictly implement the requirements of the *New Plan* and increase investment in water pollution control facilities to further reduce their grey WF (Wu et al., 2018).

Moreover, improving waste water recycling capacity is an important way to control the growth of blue WF. In Tianjin, according to current trend, the grey WF is decreasing, but the blue WF is expected to increase rapidly and will become the main components of Tianjin's future WF (Figure 10b). If no effective measures are taken to control the increase in the blue WF, the domestic blue WF and ecological blue WF will become major threats to Tianjin's water security in the future. Beijing has provided an example for Tianjin and other cities facing the threat of blue WF. From 2011 to 2016, the water use for urban greening in Beijing increased from 0.45 billion m^3 to 1.11 billion m^3, but the ecological blue WF of Beijing only increased from 0.12 billion m^3 to 0.37 billion m^3. The reclaimed water utilization rate among the ecological and industrial sectors has reached 40.2% in Beijing, which reduced the blue WF significantly. If Tianjin can improve its reclaimed water utilization rate to reach the level of Beijing, Tianjin will also eliminate the water deficit. Thus, there is an urgent need to reduce the blue WF by improving waste water recycling capacity (Li et al., 2021; Hou et al., 2021; Zhang et al., 2020). In addition, the ecological blue WF can be further reduced by improving irrigation techniques and enhancing rainwater harvesting (Gimpel et al., 2021; Silva et al., 2014; Liu and Wu, 2021).

<Insert Fig. 10 here>

5.4 Future perspectives

More research is necessary in assessing WF dynamics and water scarcity in major cities. When calculating the WF, the grey WF was not comparable due to the large difference in urban sewage discharge data before and after 2011 in the China

Statistical Yearbook. In addition, the China Statistical Yearbook after 2017 will no longer count the emissions of ammonia nitrogen and other pollutants. Thus, this study only assessed the WF dynamics of China's major cities over a short six-year period (from 2011 to 2016), which does not provide a complete picture of the urban WF changes during urbanization in China. On the other hand, when calculating the domestic blue WF and domestic grey WF, the statistics included domestic water usage and discharged sewage from residents in rural areas within the prefecture-level cities. When assessing urban water scarcity, all runoff from the upper reaches of a city's watershed was considered to be available to the city, which is not the actually the case, so the amount of water available to the city was overestimated and, therefore, the water deficit faced by the city was underestimated.

In future research, we will attempt to calculate the urban WF and assess urban water scarcity more accurately. On the one hand, more detailed statistical data could be obtained, which can be combined with urban water metabolism models to quantify the urban WF as accurately as possible and to provide a more complete picture of how the WF changes during urbanization in China (Rathnayaka et al., 2017; Qin-Ying Song et al., 2017). Information on the spatial distribution of urban water sources and water supply will be combined to more accurately assess the amount of water available for cities in terms of the actual supply and demand of urban water resources, to further reveal the water scarcity in major cities in China.

6 Conclusions

This paper calculated the dynamics of the production-based WF of China's major cities from 2011 to 2016 and provides important insights into existing research on the urban consumption-based WF. The results show that, overall, the average WF of China's major cities decreased from 13.8 billion m^3 to 10.3 billion m^3, the per capita WF decreased from 1614.8 m^3/person to 1184.0 m^3/person, the number of cities with water deficits decreased from 12 to 10, and the water shortage problem in major cities was alleviated due to the obvious reduction in grey WF. Such reduction was mainly attributed to the implementation of water pollution control policies. In the future, there is still a need to further implement pollution control policies and promote industrial upgrading to reduce the grey WF, while a series of measures are also needed to reduce the increasing domestic and ecological blue WF, for safeguarding economic development and urban environmental improvement to alleviate urban water scarcity and achieve sustainable cities.

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Data Availability Statement

All data in this article are open access data. The pollutant emission data comes from China Statistical Yearbook (http://www.stats.gov.cn/tjsj./ndsj/). The water use date from Ministry of Water Resources of China (http://www.mwr.gov.cn/sj/#tjgb)

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Table 1 Definition of urban WF from production perspective

	Indicators	Definition	Data sources
Grey WF	Industrial grey WF	The amount of water consumed to dilute industrial COD and industrial ammonia nitrogen discharged from factories to meet the Class III water standard.	China Statistical Yearbook
	Domestic grey WF	The amount of water consumed to dilute domestic COD and domestic ammonia nitrogen discharged to meet the Class III water standard.	
Blue WF	Industrial blue WF	Water consumed by industrial and mining enterprises for manufacturing, processing, cooling, air conditioning, purification, washing, etc., in the course of production, excluding reuse of water.	Water Resources Bulletin for Provinces, Municipalities and Autonomous Regions
	Domestic blue WF	Water for domestic use by urban residents and for urban public use, including water for the service and construction industries.	
	Ecological blue WF	Water for the urban environment and ecological replenishment and supplied by anthropogenic measures, including river and lake replenishment, greening and cleaning water, excluding water naturally satisfied by precipitation and runoff.	

Table 2 Comparison with existing urban WF studies

Region	Time	Calculation method	WF (m^3/person) Average	Maximum value	Minimum value	References
31 major cities in China	2011	Production-based	1618.6	2908.6	858.4	This study
	2016		1190.9	2195.6	384.8	
Chinese Cities	1992	Consumption-based	3913.0	-	-	Cai et al., 2019
	2012		2826.5	-	-	
74 major cities in the USA	2012	Consumption-based	6200.0	-	-	Chini et al., 2016
Milan, Italy	2013	Consumption-based	2058.2	-	-	Vanham and Bidoglio, 2014
Egyptian cities	2007	Consumption-based	696.3	-	-	Wahba et al., 2018
Bogotá	2014	Consumption-based	523.0	-	-	Castillo et al., 2018

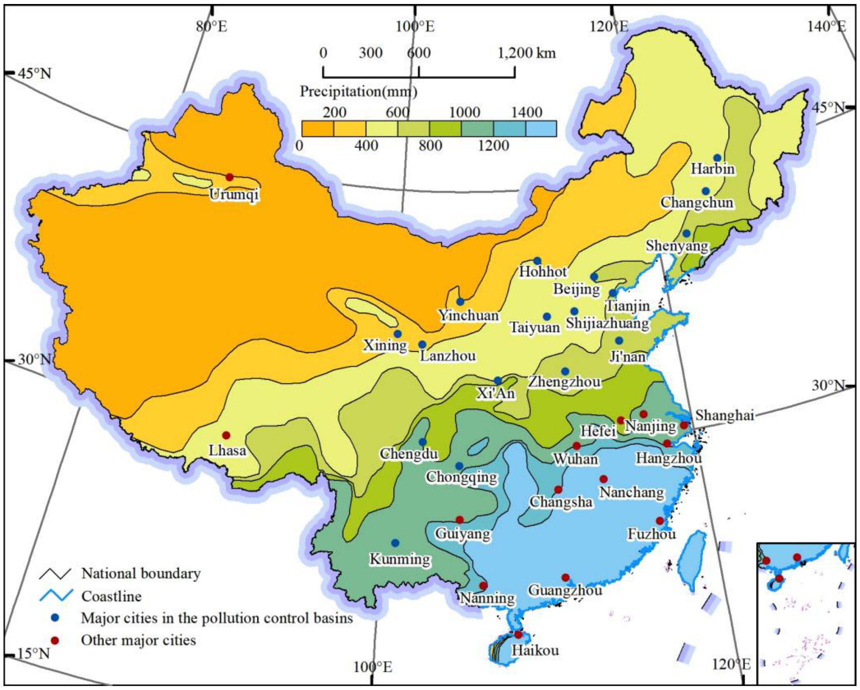

Figure 1 Study area

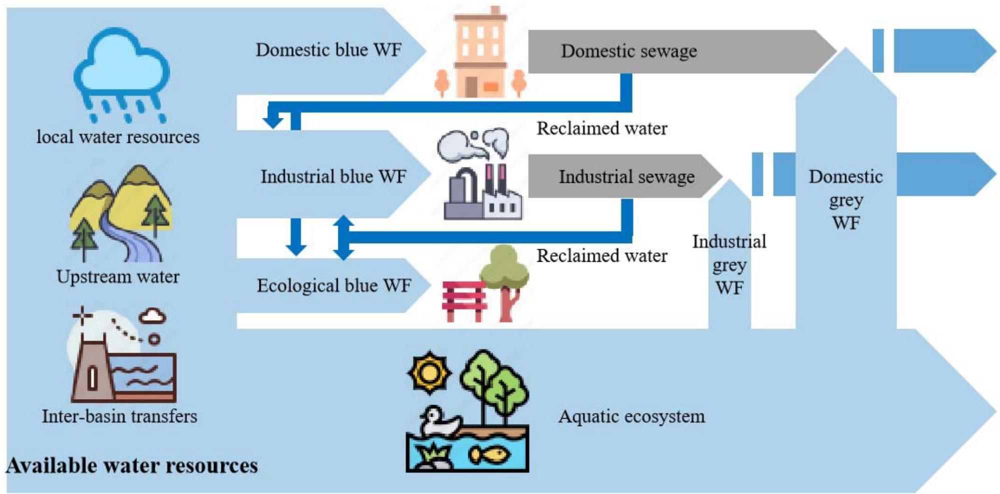

Figure 2 Diagram of urban WF from production perspective

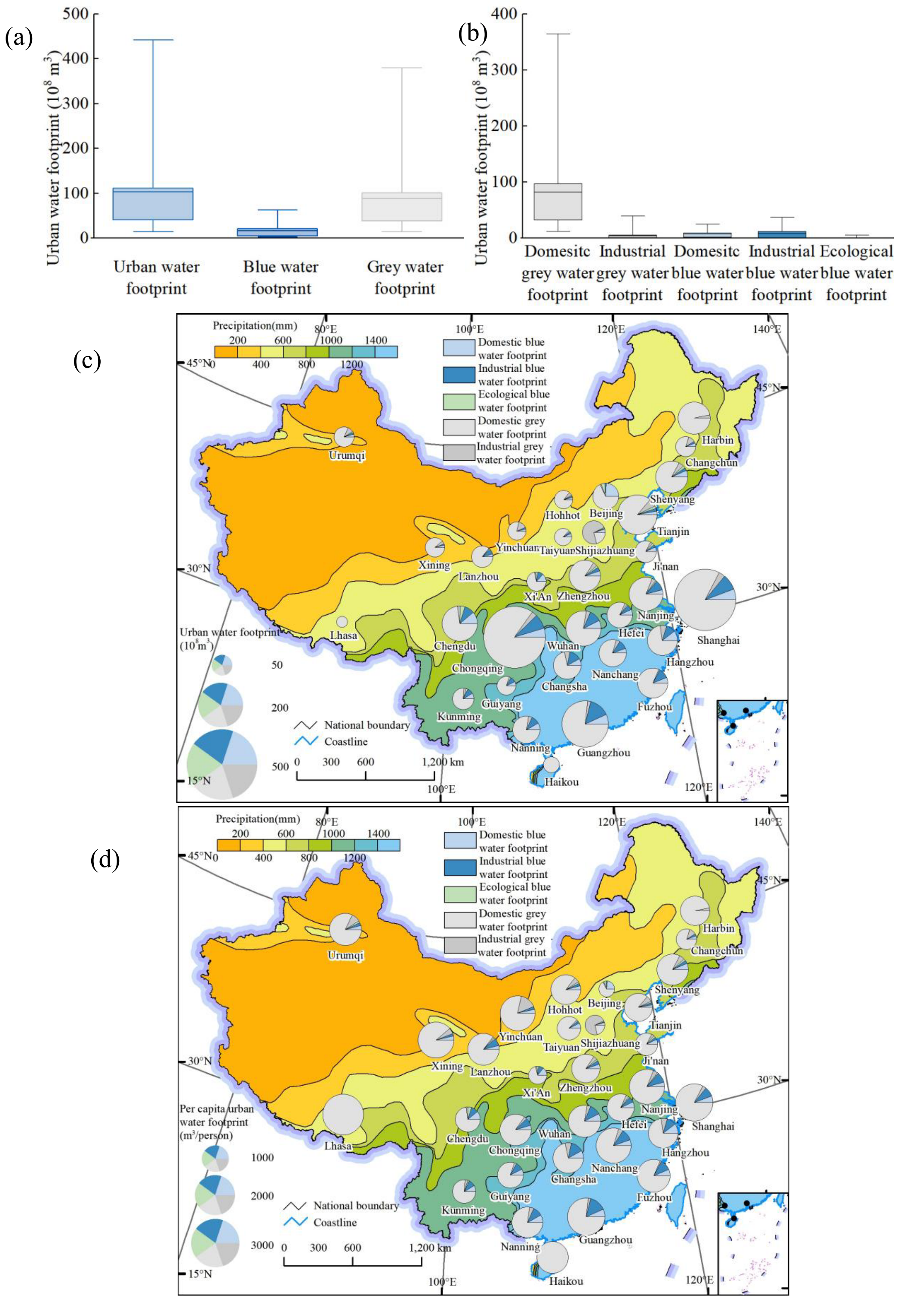

Figure 3 WF of major cities in 2016 (a) Total WF structure; (b) Sectoral WF structure; (c) Total WF by city; (d) Per capita WF by city

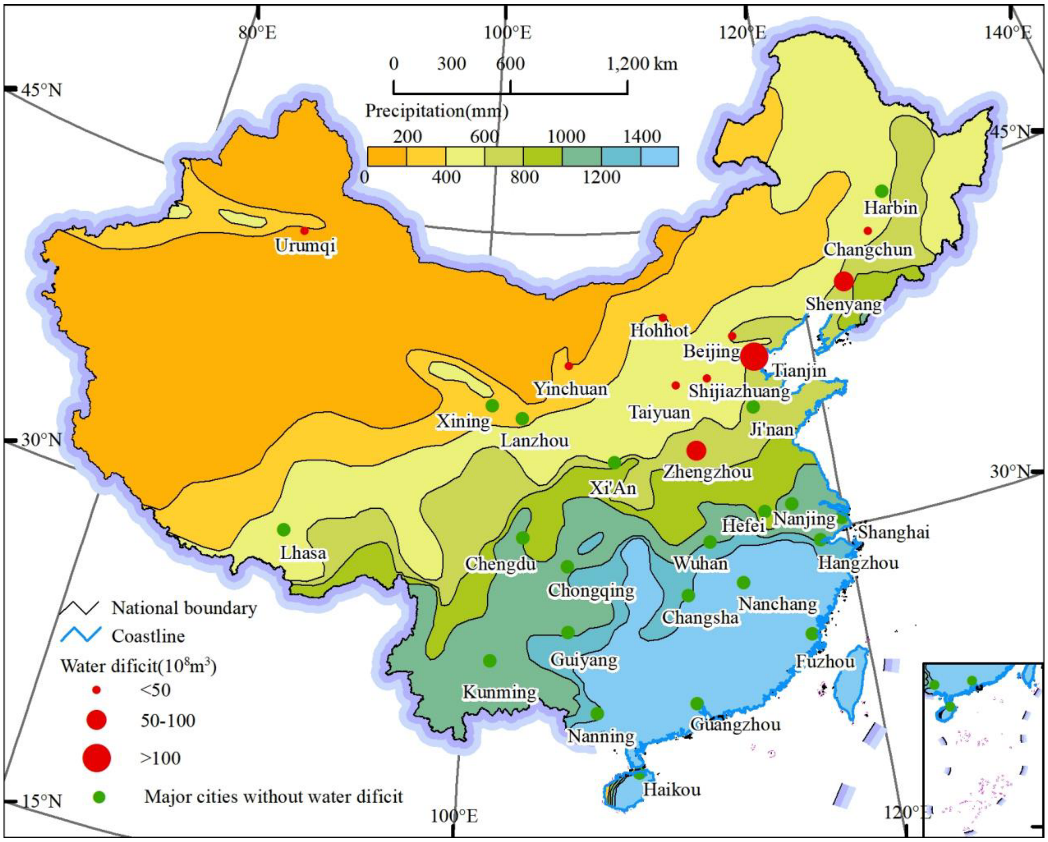

Figure 4 Water deficit of major cities in 2016

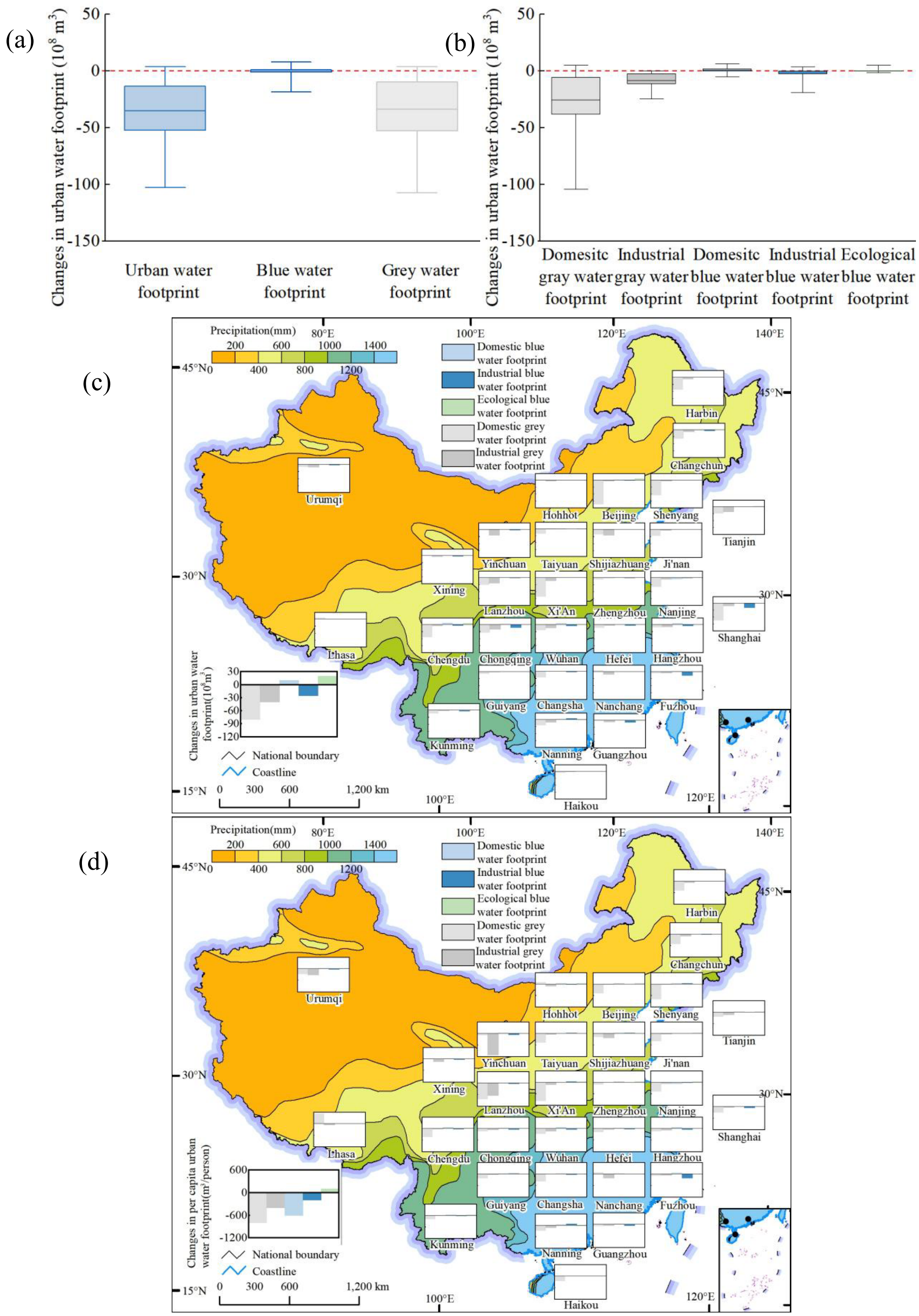

Figure 5 WF dynamics in major cities from 2011 to 2016 (a) Total WF structure; (b) Sectoral WF structure; (c) Total WF by city; (d) Per capita WF by city

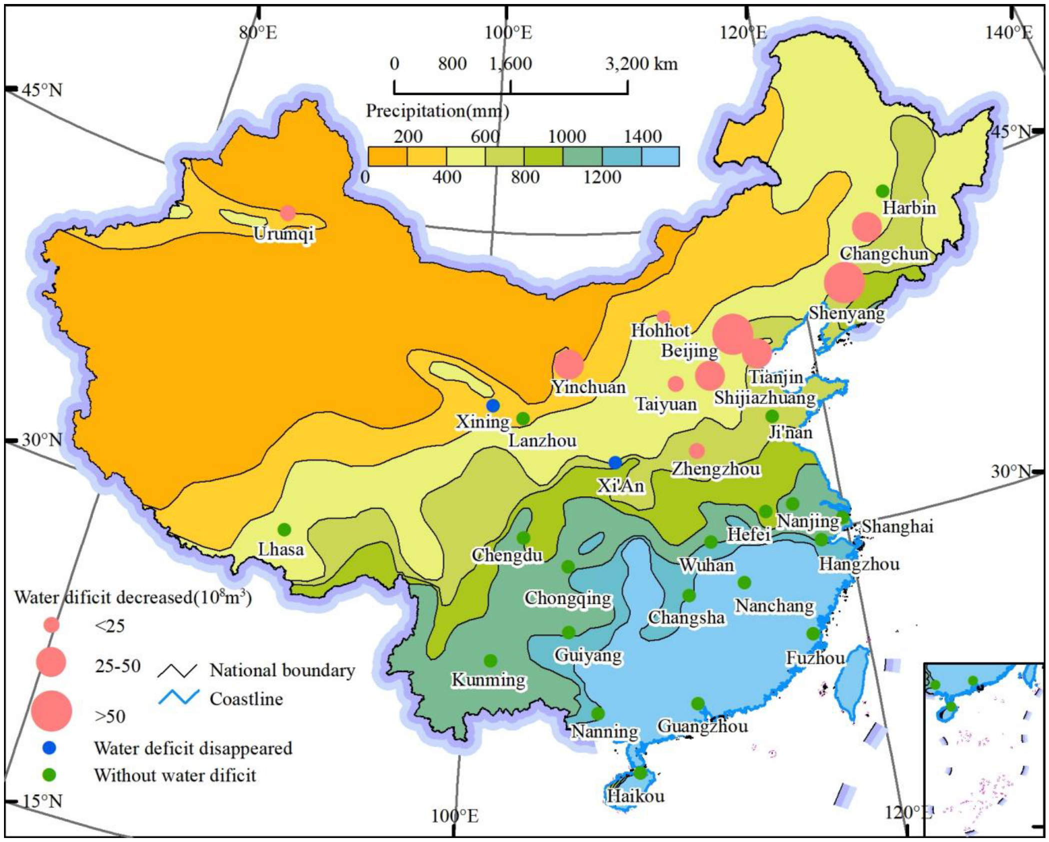

Figure 6 Water deficit dynamics in major cities from 2011 to 2016

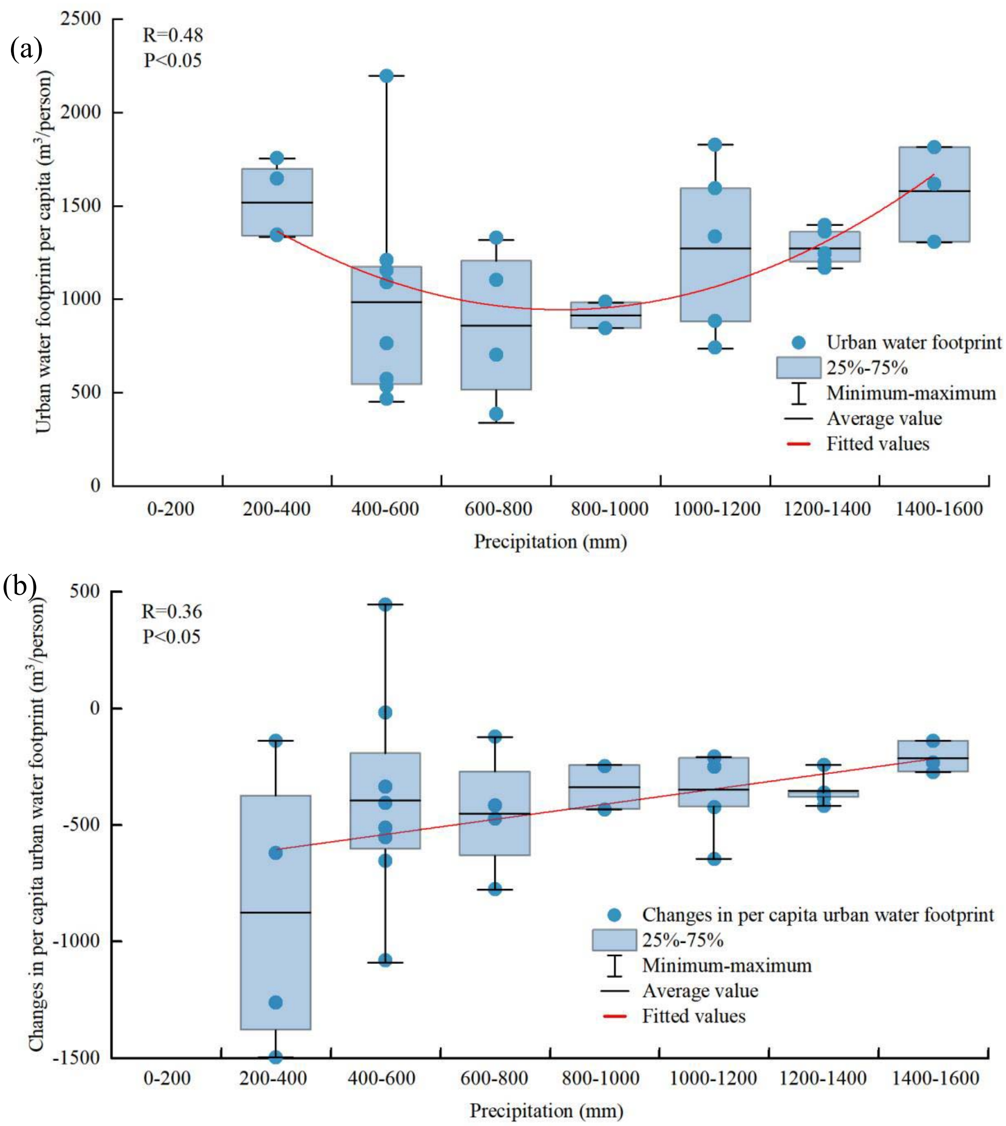

Figure 7 Urban WF distribution and change characteristics along precipitation gradients

(a) Per capita WF in 2016; (b) Per capita WF dynamics from 2011 to 2016

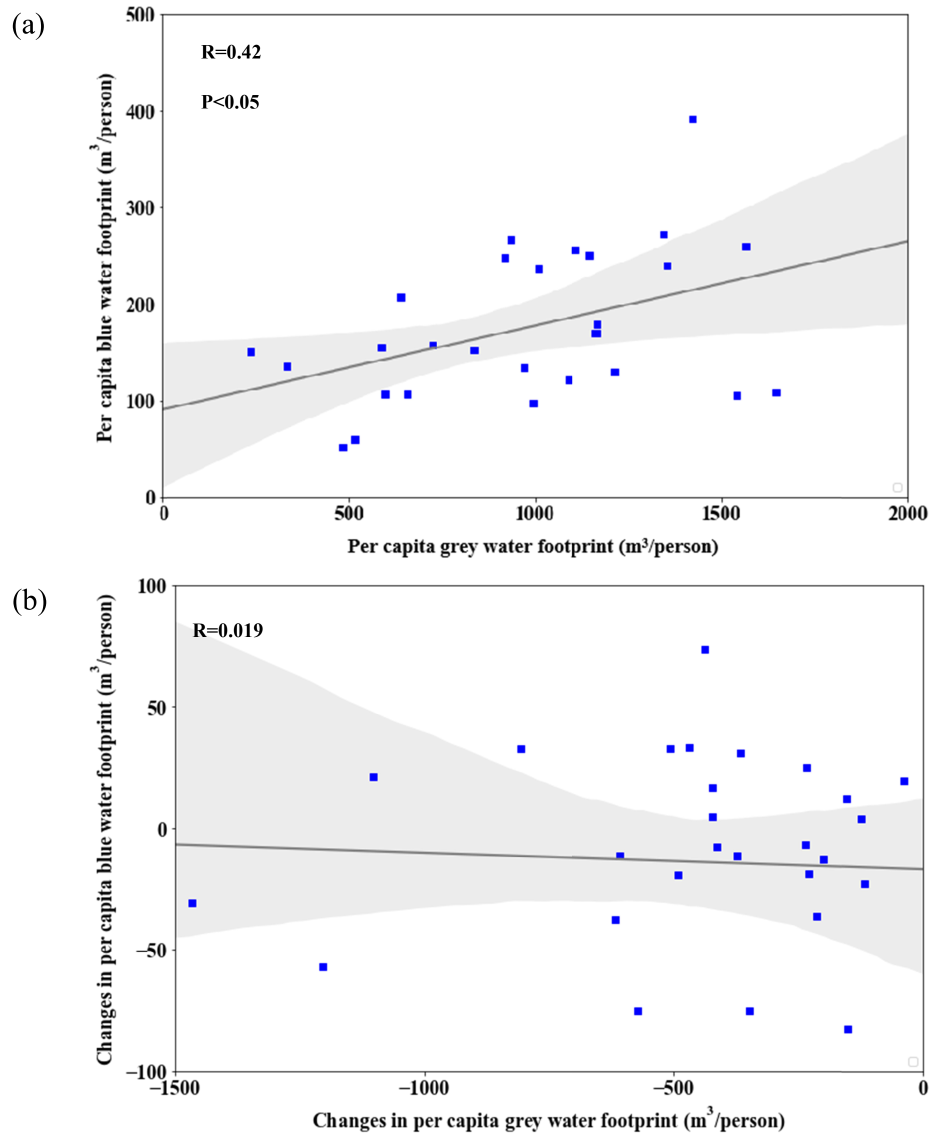

Figure 8 Relationship between blue WF and grey WF

(a) Relationship between per capita blue WF and per capita grey WF in 2016

(b) Relationship between the dynamics of the per capita blue WF and the relative dynamics of the per capita grey WF from 2011 to 2016

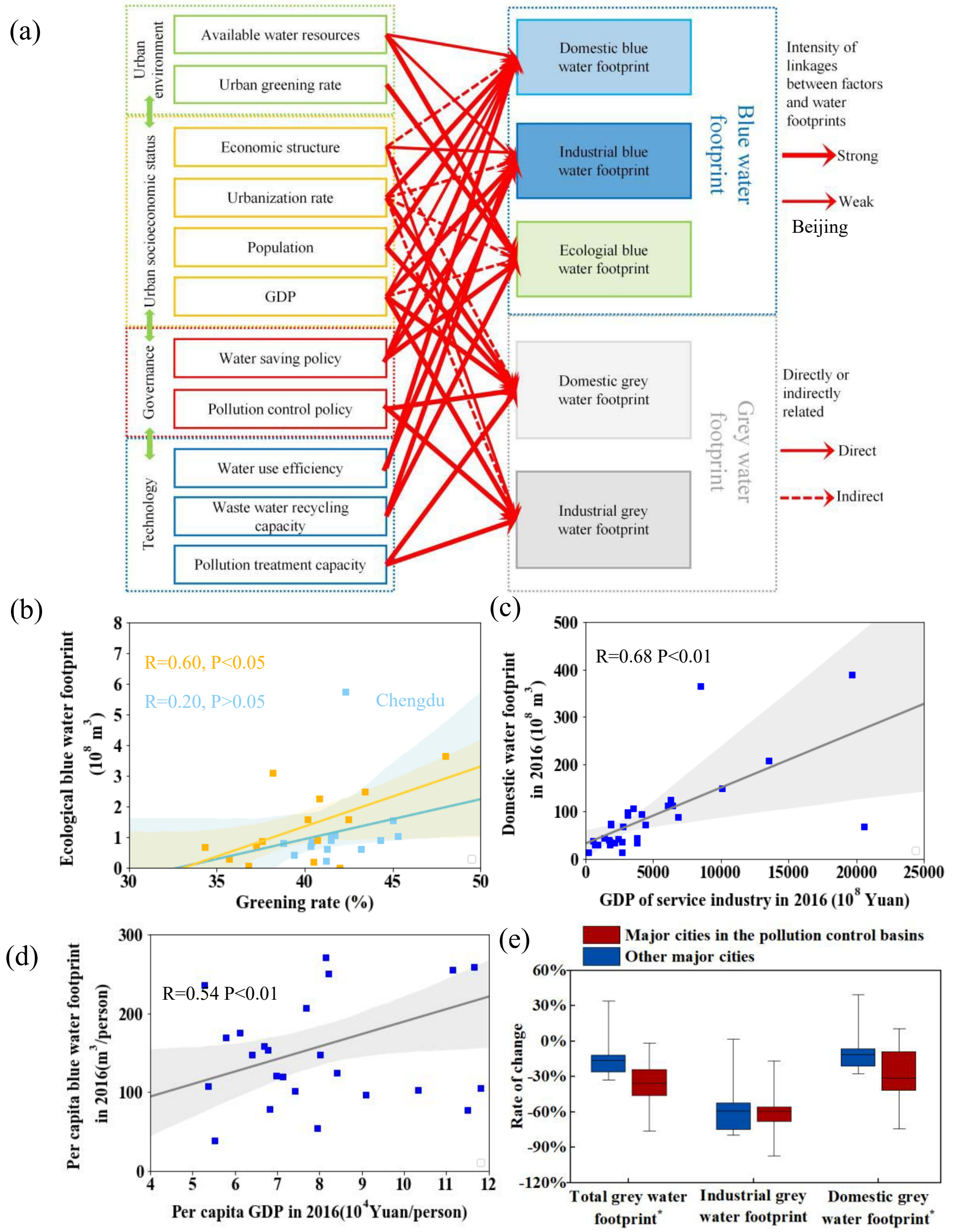

Figure 9 Factors influencing changes in WF

(a) The relationship between the main influencing factors and WF; (b) The relationship between the greening rate and the ecological blue WF in major cities. Yellow point represents the cities with an annual precipitation of less than 800mm, blue point represents more than 800mm; (c) The relationship between the GDP of service industry and the domestic WF in major cities; (d) The impact of water pollution control on the WF; (e) The relationship between the per capita GDP and the per capita blue WF in major cities

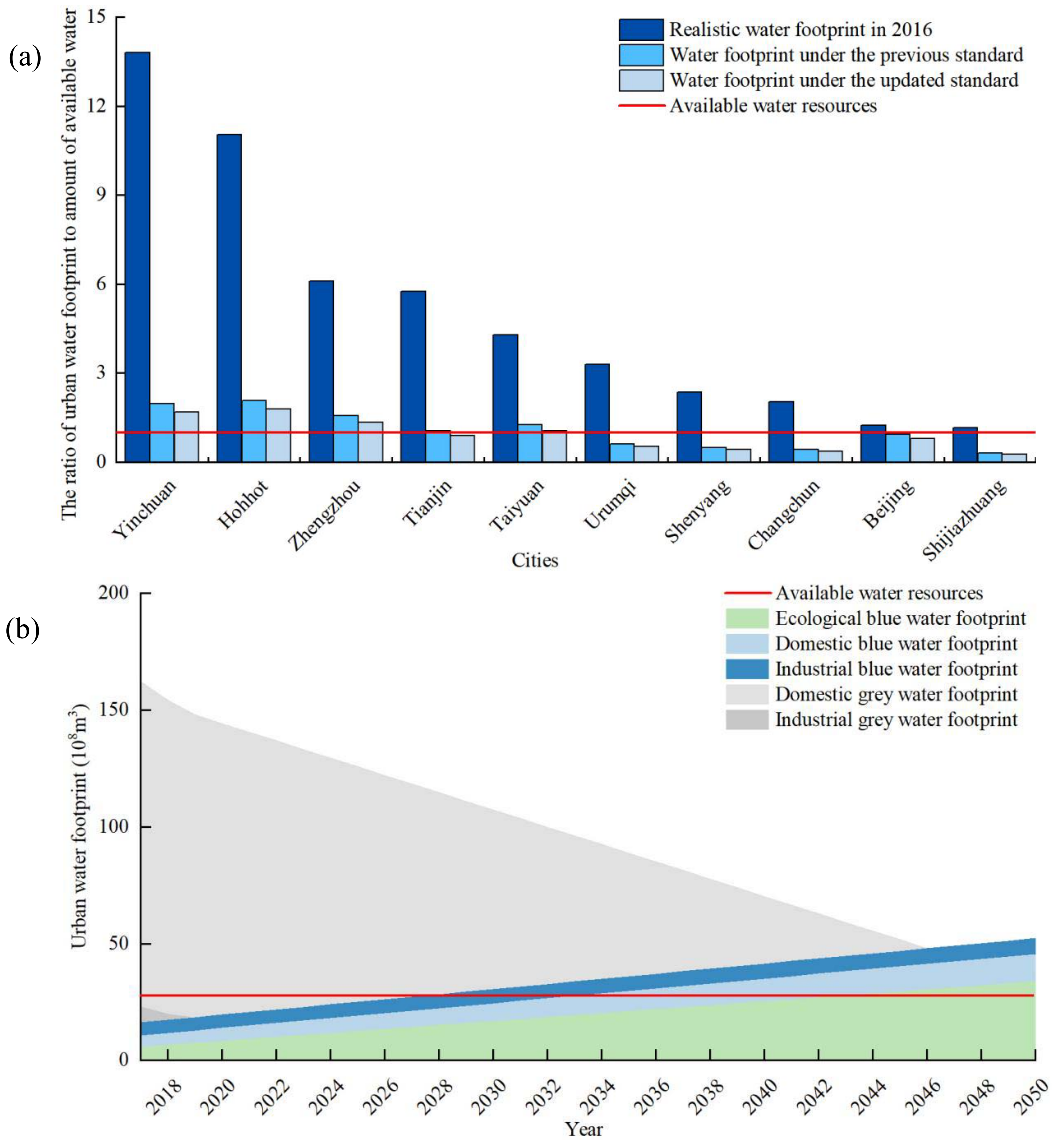

Figure 10 Projected future urban WF under different scenarios

(a)Future WF of cities facing water deficit under different discharge standards

(b) Future WF in Tianjin under the trend scenario

Note: The WF of different discharge standards is the estimated WF based on the 2016 sewage discharge and the pollutant discharge standards under the *Plan* and the *New Plan*. The column above the red line means there is a water deficit, and a column below the red line means eliminating the water deficit.